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# Improved fuel characteristics of cotton stalk, prosopis and sugarcane bagasse through torrefaction

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## ABSTRACT

Torrefaction is a rational method for improving the properties of biomass as a fuel. It consists of a slow heating of biomass in an inert atmosphere to a maximum temperature of 300 °C. Torrefaction yields a solid uniform product with lower moisture and higher energy content compared to those of the raw biomass. This work contributed to the development of torrefaction process at 300 °C for 1 h for cotton stalk, prosopis and sugarcane bagasse biomass which improved gross caloric value (27–41%), decreased moisture and volatile content (3.3–5.8% and 14–18% respectively), improved fixed carbon (9–24%) and reduced weight (27–46%). Statistically significant increase in calorific value and decrease in moisture content ($p = 0.015$ and $p = 0.024$, respectively) were observed by torrefaction of the biomass. There was a marginal decrease in bulk density being highest in cotton stalk (0.08 g/cm$^3$). Energy gain of 0.47 cal/g by torrefaction was noted in prosopis with no difference in ash content. Therefore, prosopis should be considered as potential biomass for torrefaction and can be used as biofuel. Further, torrefied biomass being hydrophobic in nature, is easy to handle during storage and transportation without significant changes in biofuel characteristics.

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## Introduction

Biomass residues have a great potential in most developing countries, since they are able to replace energy sources such as firewood. However, only a small proportion of biomass residues are being used as fuel because of their high moisture content, high polymorphism and low energy density. These troublesome characteristics increase costs for transport, handling, and storage, making the use of biomass as a fuel impractical. Drying of biomass is not sufficient since biomass regains moisture during storage and may decompose (Sridhar et al., 2007). A way to eliminate some of the disadvantages mentioned above could be the torrefaction of biomass (Felfli et al., 1998).Torrefaction involves heating biomass between 200 and 300 °C in an inert atmosphere and improves fuel characteristics as well as storage efficiency of biomass. The product of torrefaction has beneficial properties such as (i) improved heating value, low moisture content and ease of size reduction. Due to lower moisture content, it is cheaper to transport torrefied biomass, (ii) hydrophobic nature: the material does not gain humidity in storage and therefore unlike charcoal and biomass, it is stable and is resistant to fungal attack, (iii) easy burning and less smoke formation when burnt, and (iv) the product is suitable for applications such as cooking fuel, residential heating, raw material for gasification, power plant, etc.

Although the principles of torrefaction are known since 1930, currently no commercial process is available in the Indian market. Torrefaction technology has been developed during the 1980s to the phase of technical demonstration, but this was for a different market requiring different product specifications (Girard and Shah, 1991). Therefore the objectives of this study were (1) to perform torrefaction process for biomass to evaluate fuel value of biomass, (2) to analyze and compare widely available biomass like cotton stalk, prosopis and sugarcane baggase for torrefaction and (3) to develop and understand process parameters for energy density through torrefaction process which could meet requirement of end users.

## Experimental procedure

### *Biomass collection*

Cotton stalk, prosopis and sugarcane bagasse samples were collected by agriculture expert R & D team.

### *Equipment and process*

In each experiment, a fixed amount of the biomass sample was subjected to torrefaction at atmospheric pressure in absence of oxygen. A muffle furnace was heated and kept at the selected final temperature of 300 °C for 1 h and then the furnace was switched off. After the treatment, the samples were left to cool down. The collected torrefied solid products were weighed and characterized. The

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influence of the experimental conditions on the properties of the products was studied.

### *Proximate analysis*

Raw as well as torrefied biomass were analyzed for ash content, fixed carbon, moisture content, volatile matter and gross calorific value (GCV) (Speight, 2005).

### *Statistical analysis*

Raw and torrefied biomass samples each of 23 were compared for proximate analysis by paired student *t* test using statistical software SPSS (version 15). p Values less than 0.05 were consider statistically significant.

### *Energy calculation*

Energy loss or gain by torrefaction process was calculated using the following calculation procedure:

1. (GCV difference = GCV of raw biomass × raw biomass weight − GCV of torrefied biomass × torrefied biomass weight)
2. (Weight difference = raw biomass weight − torrefied biomass weight)
3. (Energy gain/loss = GCV difference/weight difference)

## Results and discussion

Figs. 1 to 7 show comparison of GCV, moisture, volatile matter, fixed carbon, weight, bulk density and ash content respectively in cotton stalk, prosopis and bagasse samples as raw biomass and torrefied biomass.

Torrefaction of biomass at 300 °C for 1 h significantly increased calorific value ($p = 0.015$, Fig. 1), decreased moisture content ($p = 0.024$, Fig. 2) and reduced weight from 27 to 46% (Fig. 3). Similar results were published using wood briquette torrefaction by Felfli et al. (2005).

Biomass is completely dried during torrefaction and after torrefaction the uptake of moisture is very limited. The main explanation of the hydrophobic nature of the biomass after torrefaction is that through the destruction of OH groups the biomass loses its capability of hydrogen bonding. Moreover, unsaturated structures are formed which are non-polar (Bergman et al., 2005). It is likely that this property is also the main reason to stop biological degradation of torrefied biomass. The most reactive biomass polymer during torrefaction is hemicellulose. After torrefaction it is converted completely to alternative char structures and volatiles. Most of the weight loss can be contributed to hemicellulose with the effect that torrefied biomass mainly consists of cellulose and lignin. In general, hemicellulose is the most reactive polymer followed by lignin and cellulose is the most thermostable. Hence the lignin content increased. Torrefaction of prosopis showed energy gain of 0.47 cal/g while cotton stalk and bagasse showed loss of energy by 2.00 and 2.93 cal/g. This suggests that prosopis has less weight loss with increase in caloric value as compared to cotton stalk and bagasse (Figs. 1 and 3). This also reflects that prosopis has less hemicellulose so that the weight loss is less during torrefaction process.

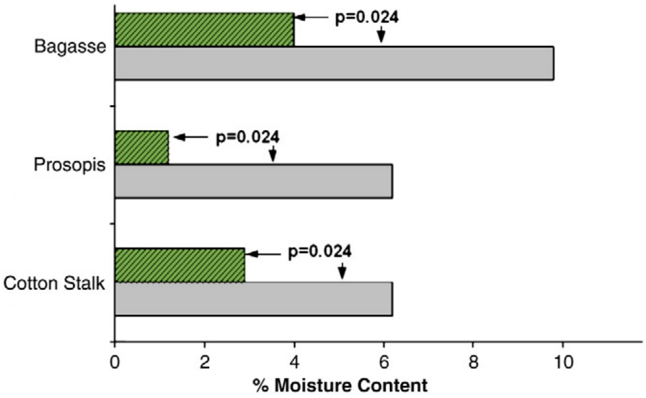

**Fig. 2.** Comparison of moisture content between raw and torrefied biomass.Torrefied vs. raw biomass, $p = 0.024$. ▨ Torrefied Biomass ☐ Raw Biomass.

Volatile matter reduced between 14 and 18% with improved fixed carbon content by 9–24% (Figs. 4 and 5 respectively). The bulk density of all biomass decreased marginally, with highest decrease in cotton stalk (0.08 g/cm$^3$, Fig. 6) while ash content increased up to 2.5% being lowest in prosopis (Fig. 7). It has been reported that during torrefaction of birch, salix, wood and straw pellets, the biomass undergoes changes in physical and chemical properties resulting into increase in fixed carbon content and energy density while the yield on a weight basis decreases (Zanzi et al., 2004).

There are temperature dependent physical and chemical changes in the torrefaction process. At temperatures of 100–150 °C, physical

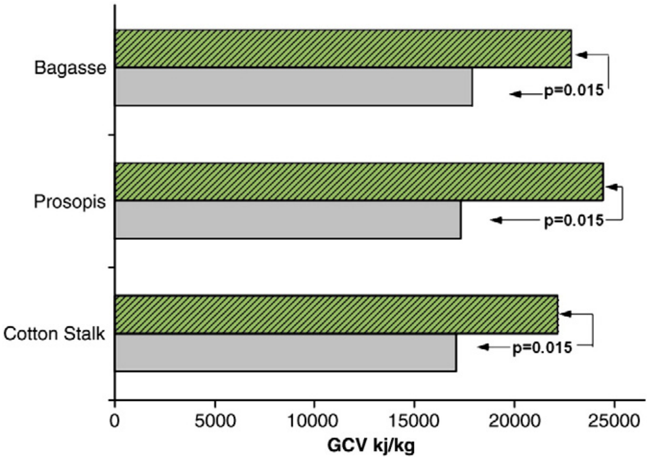

**Fig. 1.** Comparison of gross caloric value (GCV) between raw and torrefied biomass. Torrefied vs. raw biomass, $p = 0.015$. ▨ Torrefied Biomass ☐ Raw Biomass.

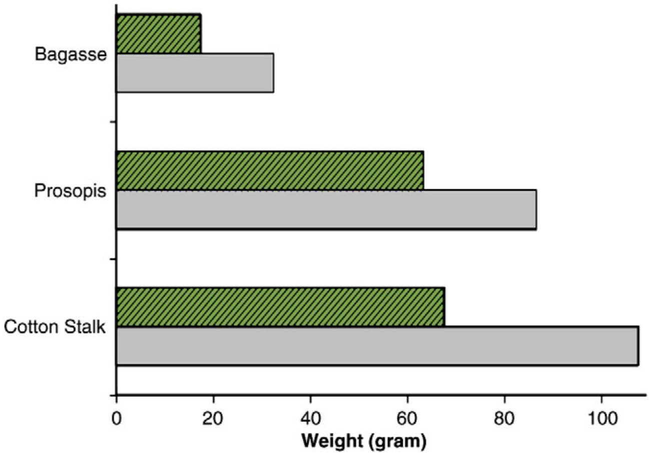

**Fig. 3.** Comparison of weight between raw and torrefied biomass. ☐ Raw Biomass ▨ Torrefied Biomass.

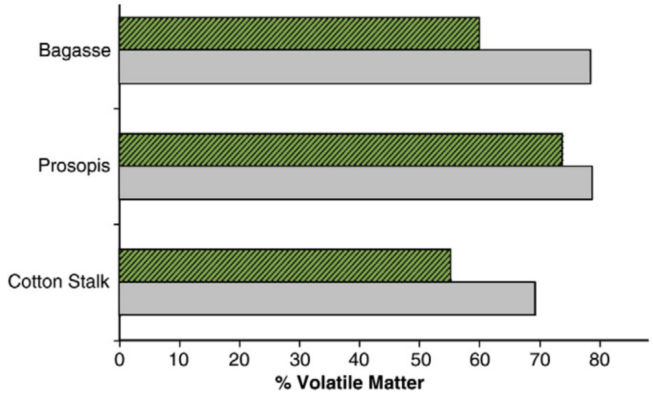

**Fig. 4.** Comparison of volatile matter between raw and torrefied biomass. ▨ Torrefied Biomass ☐ Raw Biomass.

drying of biomass occurs. Depolymerization occurs at 150–200 °C and the shortened polymers condense within the solid structure. A further increase of temperature to 200–275 °C leads to limited devolatilization and carbonization of the intact polymers and solid structures form at 200 °C. A further increase of temperature to 300 °C leads to extensive devolatilization and carbonization of the polymers. In the present study the temperature applied was 300 °C which accomplished extensive devolatization as reflected in Fig. 4. For lignin also a temperature between 125 and 150 °C is standardized in which softening of this biomass constituent occurs, a phenomenon very beneficial in the densification of biomass, as softened lignin is a good binder (Bergman, 2005). Therefore, torrefaction could be a viable method to eliminate some of the disadvantages of raw biomass as it significantly improves energy content and prevents absorption of moisture during storage.

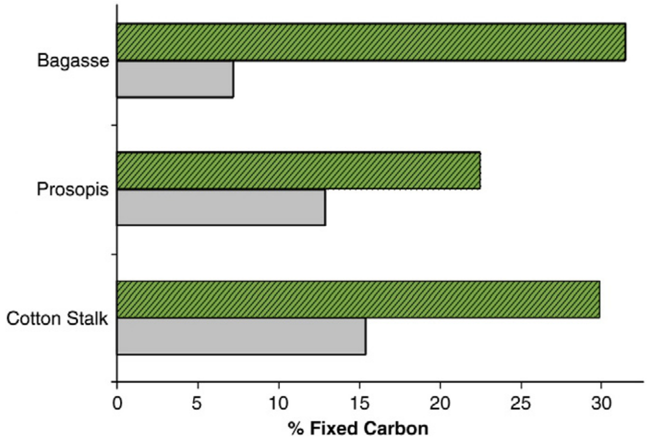

**Fig. 5.** Comparison of fixed carbon between raw and torrefied biomass. ▨ Torrefied Biomass ☐ Raw Biomass.

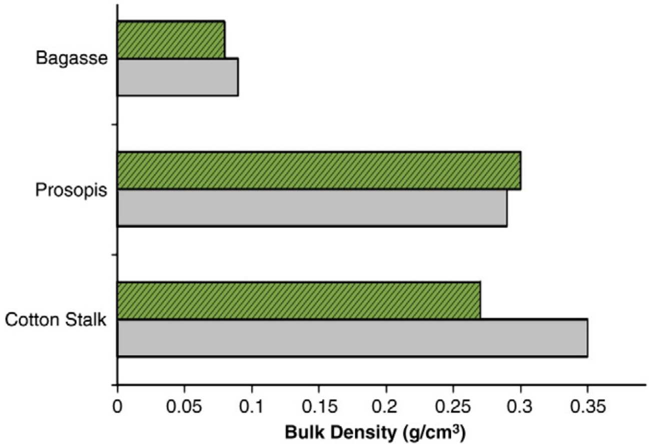

**Fig. 6.** Comparison of bulk density between raw and torrified biomass. ▨ Torrefied Biomass ☐ Raw Biomass.

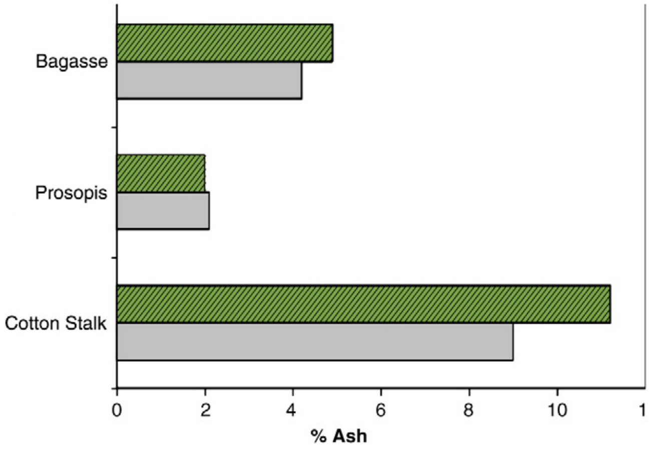

**Fig. 7.** Comparison of ash content between raw and torrefied biomass. ▨ Torrefied Biomass ☐ Raw Biomass.

## Summary and way forward

Each type of biomass has unique physical and biochemical properties. During torrefaction biomass undergoes structural changes resulting into loss of gaseous (volatile) matter. Prosopis contains less hemicellulose compared to agriculture bio-waste like cotton stalk and bagasse. This results in high caloric value, less weight loss and low ash content upon torrefaction. Furthermore, torrefaction can be an efficient technology for upgrading biomass to facilitate high level of biomass co-firing. It is recommended to continue the development of torrefaction technology by means of pilot-scale testing using efficient reactor. It is also possible to further address aspects that belong to the current phase of development in India. The grindability of biomass after torrefaction may enable higher co-firing rates in the near future. Experimental work has revealed that torrefied biomass can be produced with grindability comparable to coal and with a combustion reactivity comparable to wood. However this needs to be proven using available biomass and technology in India. Evaluation of this aspect can be done following similar approach applied in this work. Furthermore, it is recommended to evaluate the potential of torrefaction in combination with densification (pelletization), in order to minimize dust formation and to benefit from the high volumetric energy density that possibly can be achieved with respect to handling and logistics.

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